

Comparative environmental performance of semi-trailer load boxes for grain transport made of different materials

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Abstract

Background, aim, and scope Semi-trailers with load boxes are the most important mode of grain transport by land in the world. Load boxes can be produced with different materials such as: wood, steel, and synthetic material. They are responsible for effectiveness retention and quality of grains during the transport. Among the main aspects to be considered and valued when selecting materials for load boxes are the final mass of the semi-trailer, loss of grains, and mechanical properties. Environmental performance is another important aspect to be taken into account for developing and selecting new materials in this kind of application. This study presents a comparative environmental evaluation of load boxes built from two different materials (a wood panel and a three-layer synthetic (TLS) panel). Mass balance and life cycle assessment (LCA) were used in this study.

Materials and methods The TLS panel is made of polyvinyl chloride, metal, and wood sheets. The wood panel is composed of a marine plywood, protected with latex paint. Each semi-trailer is 7.1 m long and has two load boxes. Mass balance allowed the evaluation of the

productive process itself, considering the different materials used, water and energy consumption and solid waste generation. LCA was applied to evaluate the environmental impacts associated with the production, use, and end-of-life (EOL) processes for the two different types of load box panels. LCA followed the ISO 14040 standard and was performed with the SimaPro 7.0 software. The functional unit of the load boxes is defined as: to allow and to protect the transportation of 40 tons per journey of dry grains, for 10 years, traveling 120,000 km per year. The databases selected for this study were local ones produced by different authors that presented Brazilian inventories (petroleum, PVC, wood, electrical energy, steel, and natural gas). When local databases were not available, inventories from Buwal and Ecoinvent were used. Impact evaluation was performed with the Eco-indicator 95 method.

Results The mass of materials necessary to build wood panel load boxes is four times higher than the mass of material required to build the TLS panel load boxes. Furthermore, solid waste generation is ten times higher for the wood panels (on a mass basis). Water consumption is also higher for the production of the wood panel load boxes. However, the mass balance analysis showed that energy consumption during production is higher for a TLS panel load box than for the wood panel load box. The results of the LCA showed that the TLS panel load boxes provide superior environmental performance compared with wood panel load boxes. However, the wood boxes panel scored only 10.7% more impact points than the TLS panel load boxes in the LCA, considering all phases, including production, use, and end-of-life processes. The use phase is responsible for more than 96% of the total impact points for the wood panel load boxes. Impact points for the TLS load boxes are 33% higher than for the wood panel boxes during the production phase.

Discussion The TLS load boxes offer greater durability than wood panel load boxes, resulting in a smaller number

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of replacement TLS load boxes to fulfill the same functional unit. However, even considering the smaller number of replacement boxes, the difference in terms of impact points between the two types of load boxes was small. This result may seem counter-intuitive, since wood panel load box production employs more raw materials, generates more waste, and consumes more water than the TLS panel load box production. Non-standardization of the boundaries of the databases employed in the LCA is believed to be a major reason that only a small difference was found between material types in the LCA. This is particularly true with respect to the databases for disposal of residual materials, as these databases do not exist in Brazilian inventories or are not satisfactory available in other databases. Improvement of these datasets for Brazilian circumstances should be a priority.

Conclusions The TLS panel load boxes provided better overall environmental performance compared with the wood panel load boxes, considering both the mass balance analysis and LCA results. The quality of the databases employed in the analysis is a critical factor with respect to the adequacy of the LCA. Additional effort is necessary to create adequate datasets for use in Brazilian LCA, particularly with respect to waste disposal.

Keywords Comparative LCA · Environmental performance · Grain transportation · Synthetic panel · Wood panel

1 Background, aim, and scope

Semi-trailers carrying load boxes are the most important mode of grain transport by land in the world. Load boxes are responsible for retaining and maintaining the quality of the grains during transport. Load boxes can be produced with a variety of different materials including wood, steel, and polymers.

Load boxes are traditionally made of marine plywood protected with latex paint. This material has some limitations. The most important limitations of wood panel load boxes are their heavy weight, grain loss of about 10% during transportation (IBGE 2005), and their relatively short lifetime. The amount of grain loss is related to the poor conditions of the roads that affect the stability of the load boxes.

Some load boxes in Brazil are now being produced from a three-layer synthetic (TLS) panel. While the TLS panel load boxes were developed to minimize the disadvantages of wood panel load boxes, there have been no systematic evaluation of the relative advantages and disadvantages of the two types of load boxes. The TLS panel is made from 1 mm polyvinyl chloride, 0.43 mm metal sheet, and 10 mm

wood sheet. A semi-trailer with TLS load boxes is 250 kg lighter than a semi-trailer with wooden load boxes. This mass difference is due the material itself and the new way to fix the TLS panels (less material needs). In the use phase of the semi-trailer, less 250 kg represents less fuel and tire consumption.

Among the most important aspects to be considered in evaluating the materials used for load boxes are the mass of the semi-trailer, the loss of grains during transport, and the mechanical properties of the materials, including durability. Environmental performance is another important aspect that should be taken into account when comparing load box materials. However, material selection based on a mechanical evaluation in combination with environmental impact assessment is hardly ever done.

Life cycle assessment (LCA) is a suitable tool to access environmental impact of material selection or substitution (e.g. Ermolaeva et al. 2004, Bovea and Gallardo 2006). Petersen and Solberg (2003) compared the environmental impacts of substitution of wood by alternative fabrication materials, including concrete and steel, with emphasis on greenhouse gas (GHG) emissions. In their analysis, wood is a preferable alternative unless it has been treated with preservatives. Besides lower GHG emissions, wood also generates less residues and emits less SO₂ than most alternative materials. Werner and Richter (2007) presented a review about 20 years of international research on the environmental impact of LCA of wood products in the building sector. They concluded that wood products are less in fossil fuel consumption, with less potential contributions to the greenhouse effect, and generate less quantities of solid waste compared with competing products.

In this work, a comparative evaluation of the environmental performance of wood panel load boxes and a TLS panel is conducted. The evaluation included three phases: load box production, load box use, and end-of-life (EOL) process for the two types of panels. The study involved characterizing the panel production processes, performing a mass balance analysis of the panel production, surveying the water and energy consumption of the panel production process, and making an evaluation of the environmental performance using a life cycle assessment tool. A mass balance was presented in order to permit a comparison with the LCA results.

2 Materials and methods

The main steps followed in the study were: characterization of the wood panel and TLS panel load box production, data collection to perform a mass balance analysis, and to determine water and energy consumption during production; characterization of service life and EOL process;

collection of Brazilian data to develop the inventories required for the LCA, application of an LCA to assess the environmental performance of the different types of load boxes; and a comparison of the results of LCA and the mass balance to identify the preferred load box material.

The procedures and information used in the different steps of the work are described in the text below.

2.1 Semi-trailer: production of wood panel and TLS panel load boxes

The standard semi-trailer presented in Fig. 1 is 7.1 m long and is composed of a chassis and the load boxes which are the subject of this study. The total area of the panels in the load boxes for a standard semi-trailer is 53.754 m². Table 1 presents key mechanical properties (bending strength and mass per unit area) and performance indices (useful life and grain loss) of the two different load box materials.

The TLS panel has a higher mechanical resistance than the wood panel, resulting in an average service life of 7 years for TLS panel load boxes compared with 2 years for wood panel load boxes. The polyvinyl chloride (PVC) protection introduced on the corners of as well as the sides of TLS panel load box avoids the grain loss during road transport.

2.2 Mass balances, water and energy consumption for wood panel and TLS panel

A mass balance analysis was performed for the production of a set of load boxes of a standard semi-trailer (see Fig. 1). All data were collected from the production line of a company that produces the semi-trailers with both wood panel and TLS panel load boxes. The production phase for wood panels consists of receiving raw material, drilling, panel installation, latex and finishing painting, and drying. The production phase for TLS panels consists of receiving raw material, wood brushing, adhesive application, PVC and steel sheet assembling, panel pressing, and drilling.

Mass balance inputs, including the raw material used in the production, and outputs, including the finished product, production residues (wastes), and water and air emissions,

were quantified for every stage of the production process. All inputs and outputs were weighed (in kilograms) and added to the mass balance. Data used to include in the mass balance for the wood panel load box were collected during 10 days in October 2006. Data used to include in the mass balance for the TLS panel load box were collected during 2 weeks in February and July 2006.

For water and energy use, no separate systems in semi-trailer production were applied. Therefore, the following criteria were used to estimate water and energy consumption during load box production:

- Consumption of water was calculated as the water employed in air emission suppression in the painting cabins, as there is no water consumption in the others production phases.
- Energy consumption was calculated on the basis of power consumption of electric motors employed in each phase of panels and semi-trailer production. The nominal capacity of all equipment used for the wood panel production process is 119 kWh and 190 kWh for the TLS production process.

2.3 LCA performance for synthetic and wood panels

The goal of this study was to undertake a comparative LCA aiming at researching the differences of the environmental impact for two different materials (wood and TLS panels) used in semi-trailer load boxes for grain transport.

The scope of this study considered the necessity to evaluate the environmental aspects involved in two load box designs (wood panel load box and TLS panel load box) for the transport of dry grain on a semi-trailer.

In order to evaluate and compare the environmental performance of the materials studied, a function had to be set to the semi-trailer system. The functional unit is defined as: the protection and transportation of 40 tons of dry grain per trip, traveling 120,000 km a year for 10 years.

As the service life of TLS panels is 7 years, 1.43 replacements are needed for providing the functional unit. For wood panels, whose useful life is 2 years, five

Fig. 1 Semi-trailer load box design

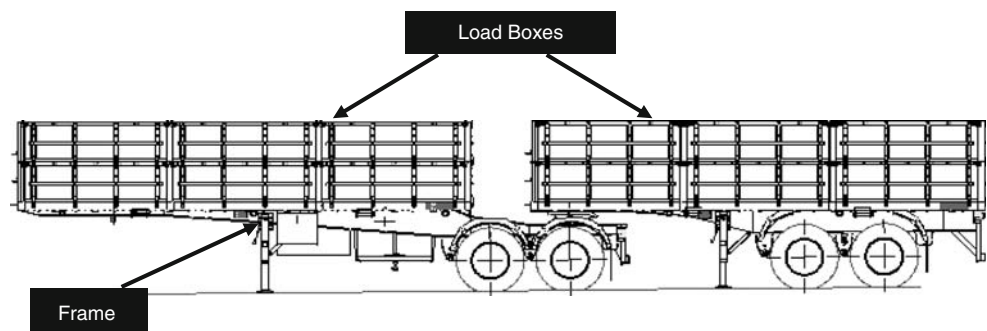


Table 1 Mechanical and other properties of wood and TLS panels

Parameter	Wood panel	TLS panel	References
Bending strength (N/m ²)	6,174	8,820	–
Panel mass per area (kg/m ²)	10.5	9.2	–
Useful life (year)	2	7	–
Grain loss (%)	10	0	IBGE (2005)

replacements are necessary for providing the functional unit.

LCA according to the ISO 14040 series of standards (ABNT 2001, 2004a,b, 2005) was applied to evaluate the environmental impacts associated with production, load box use phase and end-of-life processes for the two different types of load box panel. These phases are defined as follows:

- Production, includes production of main materials and components and the required upstream processes (e.g., production of the fuels required for the production of the materials and mining the ores) for the load boxes.
- The use phase included the fuel (diesel) required for grain transportation by a vehicle consuming 1 l of fuel per 2 km (estimated consumption in Freitas 2004) and the required upstream processes. The TLS panel load box semi-trailer is 250 kg lighter and provides 10% less grain loss than the wood panel load box semi-trailer. Both of these factors were translated into less fuel consumed by the TLS panel load box semi-trailer to transport the same quantity of grains set in the functional unit. The TLS panel semi-trailer consumes 123,751 l less diesel oil than the wood box trailer during transport of the functional unit of grains compared with the wood semi-trailer.
- For the end-of-life phase, the wood panel EOL is considered incinerated and the TLS panel is considered landfilled in line with the most frequent solutions adopted in Brazil for this kind of residue (Hillig et al. 2004). The databases for the waste disposal phase are not as complete as those for the production phase because there is no Brazilian database for residues. Proxy processes from international databases were used instead (see above).

The system flow chart including the systems boundary of the LCA is presented in Fig. 2.

The subsystems represented with solid lines in Fig. 2a were considered in the LCA, and the one represented by dashed lines were not considered due to the lack of inventory data. During the manufacturing phase for the wood panel load box (item 1 in Fig. 2a), the raw material inputs were divided in two: panel assembly (1.1) and panel painting (1.2). The outputs of these phases comprise gaseous emissions (xylene), painting residues, and liquid

emissions. During the use phase (2), the input considered was diesel oil. Other consumables such as tires were not taken into account. In the EOL phase (item 3 in Fig. 2), the incineration of wood was considered as the discarding option.

The manufacturing phase for the TLS panel load box (item 1 in Fig. 2b) had the following input of raw materials: reforested wood, PVC, and steel. For the assembly (1.1) of the panels inputs considered were energy and adhesive. The inputs of drill bits, paper, acetone, cleaner, screws, nuts, and rubber were not included due to the lack of information regarding these items. During the assembly (1.1), solid waste was generated but not taken into account. For the painting, paint input and resulting residues (liquid and gaseous emissions) were fully included in the LCA. Diesel oil was also considered for the use phase (2) but other consumables were again not considered. In the EOL phase wood, PVC and steel are considered as to be disposed in landfills.

The LCA was performed with the SimaPro 7.0 software (Pré Consultant 2006). Local databases (databases developed from Brazilian inventories) were employed where available, i.e., petrol, diesel oil, fuel oil, rock salt, marine salt, PVC (Borges 2004), native wood, reforested wood (Brugnara 2001), steel, electric energy (Coltro et al. 2003), and natural gas (Kulay 2004). When local data were not available, inventory data from Buwal (Pré Consultant 2004a), ETH-ESU (Pré Consultant 2004b) and Ecoinvent (Frischknecht et al. 2007) were used.

Eco-indicator 95 (EI 95) was used for the environmental impact assessment, taking into account carcinogenic substances, heavy metals, energy resources, solid wastes, climate change, ozone layer depletion, water ecotoxicity, human toxicity, and acidification/eutrophication. This impact assessment method aggregates the emissions from the product life cycle into these impact categories and further into a single weighted score called eco-indicator.

3 Results and discussion

3.1 Mass balance to evaluate comparative environmental performance of load boxes

Table 2 presents the mass balance results for wood panel and TLS panel load boxes.

Fig. 2 LCA flow charts including system boundaries with regards to production, use phase and EOL for (a) wood panel load box and (b) TLS panel load box

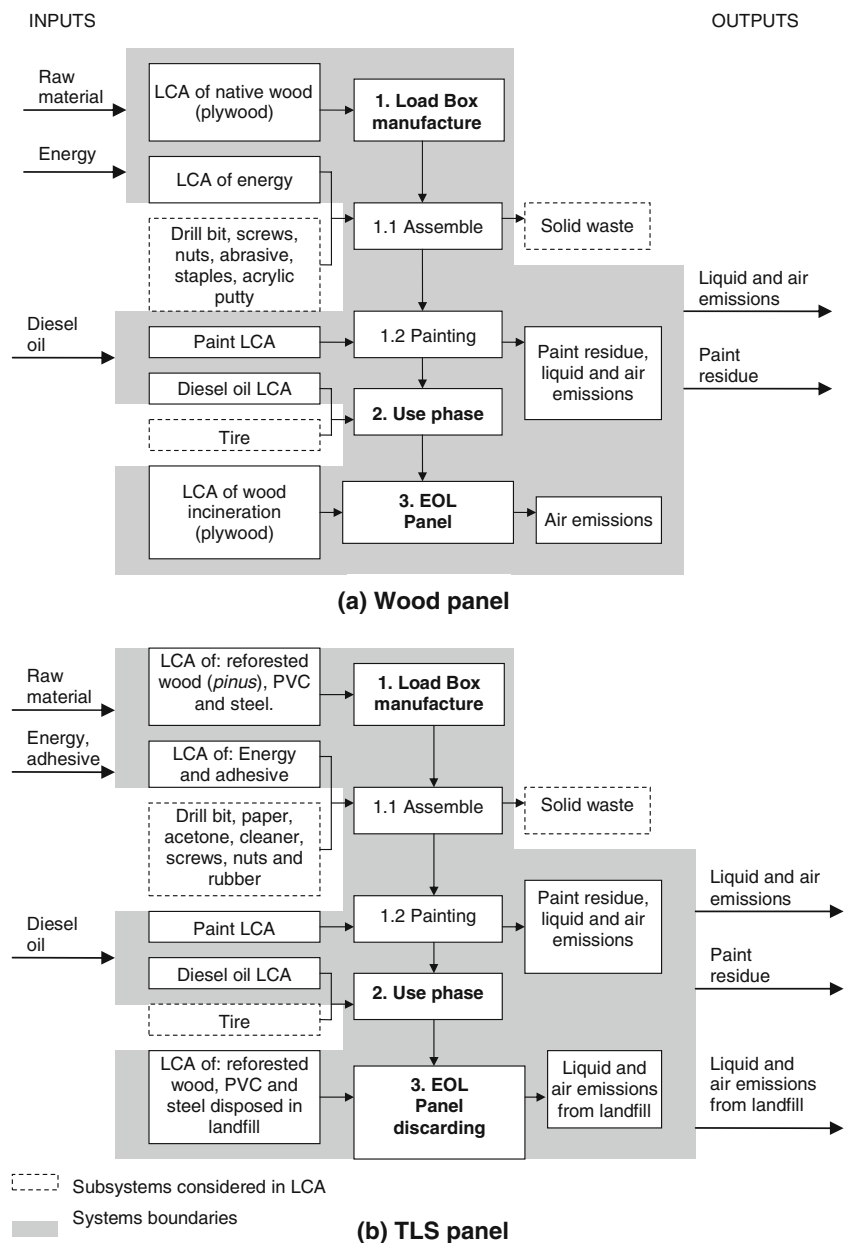


Table 2 shows all inputs to the production process of the load boxes as well as the solid waste generation and energy and water consumption. The mass of raw and others materials necessary to build the wood panel load boxes is four times higher than used for the TLS panel load boxes. The amount of solid waste generated during the production of the wood panel load box is approximately ten times

higher than the amount of solid waste generated during the production of TLS panel load boxes. Water consumption was 250 m³ higher for the production of the wood panel than for the TLS panel load boxes. On the other hand, energy consumption of the production of TLS panel load boxes was higher than for the wood load box production by 26%. The TLS panel production process is more automated

Table 2 Comparative mass balance for the functional unit during the production phase

Semi-trailer load box	Raw material and others inputs (kg)	Solid waste generation (kg)	Water consumption (m ³)	Energy consumption (kWh)
Wood panel	4,085.95	140.80	321.30	46.00
TLS panel	1,034.30	14.74	72.11	58.10

than wood panel production process, leading to this higher energy consumption.

The automated TLS production process reduced the number of manual operations compared with the wood panel process. Automation reduces processes errors. Consequently, there was less solid waste generated during TLS panel production compared with wood panel production. In global terms, through mass balance evaluation, TLS load box production is more favorable from an environmental performance perspective than wood panel load box production.

3.2 Comparative environmental performance of load boxes with LCA

The total impacts of each LCA phase, as well as the emissions for the functional unit for each type of load box are provided in Table 3.

The global impact score for the life cycle of a wood panel load box equaled 321.66 points compared to 287.27 points for the TLS load box. These results show that the TLS panel load boxes provide superior environmental performance compared to wood panel load boxes. However, the difference in impact points between the wood boxes

panel load boxes and the TLS panel load boxes was only 10.7%. This relatively close impact score for the two types of load boxes was unexpected considering that the mass balance analysis showed that wood panel load box production uses more raw materials, generates more waste and consumes more water than TLS panel load box production.

The relatively close LCA score between the two types of load boxes may be due, in part, to the non-standardized definition of the boundaries of the LCA databases. Standardization in inventories is a problem faced by LCA practitioners. The boundaries of the steel production inventory database are more comprehensive than those of other databases used in this study. The broader boundaries employed for the steel production inventory could be the reason to the discrepancy between the mass balance and LCA results. Reap et al. (2008), in their review of LCA problems, ranked boundary selection as a very serious problem that may interfere in LCA results and that remains unsolved. The authors believe that standardization of system boundaries in databases is a critical problem that requires particular attention.

The results of the analysis show that the greatest environmental impact of load boxes under consideration

Table 3 Comparative LCA for wood and TLS semi-trailer

	Process	Units	Wood panel load box	TLS panel load box	Difference points for wood panel	Difference percentual points (%)
Production phase	Paint ETH	Pt	4.4534	0.5614	x	x
	Natural gas Brazil	Pt	x	4.9194	x	x
	Coal to industrial heating	Pt	x	0.5526	x	x
	PVC Brazil	Pt	x	0.4894	x	x
	Electricity Brazil	Pt	0.0462	0.0517	x	x
	Raw steel Brazil 2004	Pt	x	0.2282	x	x
	Diesel Brazil	Pt	0.0929	0.0046	x	x
	Coal FAL	Pt	x	0.0264	x	x
	Poliol-polieter A	Pt	x	0.0109	x	x
	TDI A	Pt	x	0.0048	x	x
	Electricity PUR A	Pt	x	0.0022	x	x
	Feeding volume of inputs for PUR	Pt	x	7.7×10^{-5}	x	x
	Total impact of production phase	Pt	4.5926	6.8541	−2.2615	−6.57
Use phase	Diesel Brazil	Pt	313.4118	280.1181	x	x
	Total impact of use phase	Pt	313.4118	280.1181	33.2937	96.84
EOL phase	Wood to high active chemical landfill	Pt	x	0.2964	x	x
	Final disposal of PVC packaging waste in a landfill	Pt	x	0.0130	x	x
	Steel to landfill S	Pt	x	0.0003	x	x
	Wood ash mixed to municipal waste incinerator	Pt	3.6573	x	x	x
	Total impact of EOL phase	Pt	3.6573	0.3098	3.3475	9.73
	Total impact	Pt	321.6617	287.2757	34.3797	100

x not applicable, Pt points of impact

occurs during the use phase followed by the production phase, which explains 96% of the difference in impact points between the two alternatives is in the use phase (see Table 3). This difference is primarily due to the combustion of fossil fuels and their consequent emissions. As fuel consumption is a function of vehicle weight, the lighter TLS panel load box provides better environmental performance than the wood load box in the use phase. The lower grain loss also contributes to lower fuel consumption by reducing the amount of travel (and consequently fuel consumption).

TLS panel load box was assigned 0.30 impact points, and the wood panel load box was assigned 3.65 impact points for the EOL phase. The greater number of replacements necessary to fulfill the functional unit for a wood panel load box compared with the TLS panel load box was a significant factor contributing to the larger EOL impact for the wood panel load boxes. Unfortunately, databases for waste treatment and disposal have not yet been organized for Latin America. Therefore, inventory databases selected for EOL scenarios were from Europe, resulting in a considerable lack of representativeness of these processes.

Furthermore, the potential recyclability of TLS panel load box has not taken into account in this study.

LCA results by EI 95 impact categories are shown in Fig. 3.

The pesticides and ozone layer depletion categories showed no impact for either type load boxes. The highest impacts were attributed to energy resources followed by global warming, acidification, winter smog, solid waste, summer smog, and eutrophication. Wood panel load boxes showed higher impacts than TLS panel load boxes in all of these categories. Carcinogens and heavy metals had very small impact values that are not easily distinguished in Fig. 3. But the impacts of these two

categories were higher for the TLS panel load box than for the wood panel load box.

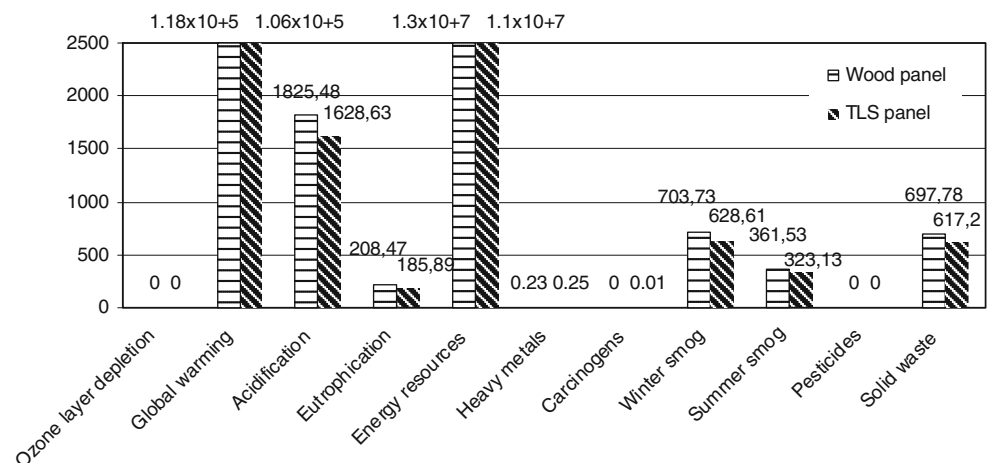
3.3 LCA applied to materials selection

In order to perform this study, the authors had to deal with the lack of local or regional inventory databases, especially for EOL scenarios. In these cases, assumptions and simplification had to be made to integrate the available databases into the LCA. This is not an ideal situation; in some cases, it renders LCA unfeasible or produces unreal results and interferes in choosing materials (Ekvall et al. 2005).

Therefore, it is very important to consolidate database inventories in order to produce reliable LCA and to introduce life cycle thinking in Brazilian industry. This consolidation will permit environmental performance analysis of processes and products that can positively influence in their design. While some inventories are already available (e.g., electric power, natural gas, fuels, and steel) the system boundaries and other methodological settings like allocation vary significantly among these inventories. This is a limitation that can produce unreliable results in LCA studies. The boundaries of each inventory have to be very clearly and consistently set to avoid distorted results (ABNT 2001) especially when the intended objective is to compare options. Furthermore, the selection of impact assessment method must be based on the relevance of the categories for the product to be assessed, as Bovea and Gallardo (2006) have demonstrated in their comparison of three different impact assessment methods. Impact assessment results can directly influence the interpretation and conclusions of an LCA.

In the case presented herein, mass balance provided a contrast with LCA results. Mass balance analysis is known

Fig. 3 Eco-indicator 95 categories applied to comparative LCA of wood and TLS panel load boxes



Units: Ozone layer depletion (eq kg CFC11), global warming (eq kg CO₂), acidification (eq kg SO₂), eutrophication (eq kg PO₄), energy resources (MJ LHV), heavy metal (eq kg PB), carcinogens (eq kg B(a)P), winter smog (eq kg SPM), summer smog (eq kg C₂H₄), pesticides (eq kg active substance), solid waste (kg).

and used by several industries, particularly to evaluate manufacturing processes, and—if carried out properly with present reliable data—enables sound decisions to reduce waste generation (Coltro et al. 2006). While the LCA impact scores are relatively close for the two alternatives (within 11%), the mass balance analysis shows that the TLS panel load box provides better environmental performance than the wood panel load box. However, mass balance analysis does not consider upstream processes, and the upstream processes can substantially influence the comparison. In the case presented herein, the upstream processes associated with steel production make the TLS panel load box considerably less favorable.

Local database created for this work will enable the development of other studies especially on the use of composite materials in Brazil. There is an increasing tendency for industries to use this kind of material because it can be engineered to have a variety of different characteristics and thereby fulfill different functions.

LCA has proved to be a useful tool for materials selection in the context of industry because it takes into account environmental performance in a manner that can be associated with economic studies. LCA permits a complete analysis of the factors associated with production and use that surpasses the traditional point of view of industry regarding production. As LCA considers impacts from a broader perspective, from raw material extraction to waste management it can make an industry a more sustainable and environmental responsible business. Furthermore, the industry that is best equipped to deal with all the phases of material use and costs will be more competitive in the long run.

4 Conclusions

LCA and mass balance analysis were applied to evaluate the substitution of wood panel load boxes for TLS panel load boxes to transport grains by semi-trailer. Mass balance results showed that during the production phase the TLS panel load box consumes less water, generates less residues, and consumes less raw material. The only category in which the wood panel load box showed better performance in the mass balance analysis was energy consumption because the automation associated with TLS panel production raised the level of energy consumption.

LCA results also showed that, in general, the TLS panel load box had less environmental impact. Nevertheless, in the production phase the TLS panel load box had a greater impact than the wood panel load box. In both the use and EOL phases, TLS panel load box showed better results than wood panel load box and the lower weight leads directly to less fuel consumption and better environmental perfor-

mance. In these EOL scenarios, the TLS panel load box had less environmental impacts due mainly to the lower number of panel replacements that are necessary during the life of the TLS load box compared with the wood panel load box.

The different results shown for the production phase between LCA and mass balance analysis are due to the upstream processes that are considered by LCA but are not considered in mass balance analysis. One deficiency with the LCA is that local data sets were not available for all relevant processes.

Environmental analysis of material substitution in the production of load boxes demonstrated that the TLS material provides environmental benefits. LCA proved to be a suitable tool to evaluate material selection or substitution for this case.

5 Recommendations and perspectives

In order for LCA to be applicable to the selection of materials with appropriate environmental attributes, it is necessary to standardize the procedures for the LCA inventory development and improve the databases associated with the region where the materials involved are produced, in this case Brazil.

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